管内伝播マイクロ波を用いた配管広域探傷技術の開発

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論文内容要旨

The maintenance of piping systems is an important concern in many industries to secure the reliability of these systems. Although the major existing inspection methods for flaws inside pipes, such as ultrasonic and eddy current testing, are highly accurate at detecting defects, they are also costly and require long inspection times. Therefore, a quicker and more efficient nondestructive testing (NDT) method must be developed to inspect long piping systems. An NDT technique using microwaves has been studied as one such inspection method. In this method, the transmission and reflection of microwaves propagating inside a metal pipe are used to detect flaws appearing on its inner surface. Because microwaves can propagate over a long distance in a metal pipe with little attenuation, the method is suitable for quickly inspecting long piping systems.

Earlier studies have demonstrated that this method can detect and evaluate wall thinning by analysing the transmission and reflection of microwaves propagating inside a metal pipe. Additionally, the time-of-flight and the amplitude of reflection were shown to be well-correlated with the location and volume of flaws, respectively. These results suggested that the technique could be applied to larger-diameter pipes through experimental studies and numerical evaluations of the electromagnetic fields inside pipes. Because earlier studies have revealed the possible application of this technique to pipes in general, the present study addresses the following basic issues to show the validity of the method.

(1) Development of a generalized approach for applying the method to a pipe of arbitrary diameter

(2) Evaluation of microwave attenuation in a long pipe and the limit of detection distance

(3) Experimental evaluation of the method's applicability to crack detection

(4) Numerical evaluation of the method's applicability to bent pipes

Chapter 1 is the introduction of this study, which provides a background, outlines earlier studies and discusses

the specific purpose.

Chapter 2 gives the theoretical background of the nondestructive microwave testing method for flaw detection in metal pipes. Section 2.1 gives the general theory of microwaves inside a waveguide. First, Maxwell's equations and the electromagnetic wave equation in a waveguide are explained. Second, an electromagnetic wave inside a conductor and the velocity of an electromagnetic wave inside a waveguide are shown. Finally, electromagnetic waves inside circular and coaxial waveguides are shown. Section 2.2 discusses the theory of the Fourier transform. Section 2.3 gives the theory of the numerical simulation used in this study. Section 2.4 describes the test equipment used in this study. Section 2.5 introduces the signal processing method which compensates the dispersion of microwave inside pipes.

Chapter 3 investigates the first issue, the development of a generalized approach for flaw detection inside an arbitrary-diameter pipe, through optimizing a microwave excitation probe that introduces microwaves into a pipe. An optimization parameter was proposed based on the transmission characteristics obtained by three-dimensional finite element simulations. The numerical simulations of the electromagnetic fields for several microwave probe profiles revealed that the reflected microwaves at the probe were much smaller for a semielliptical microwave probe in large-diameter pipes. Microwaves of the TM_{01} mode also propagated dominantly inside the pipes, independent of sweeping frequency. However, both the plate-structure and semielliptical probes showed greater transmission in small-diameter pipes. Experimental verifications were consequently conducted using an optimized microwave probe for straight brass pipes with inner diameters of 11.0, 19.0, 39.0 and 57.5 mm. The results showed that much clearer signals due to wall thinning were obtained using the semielliptical probe than with the conventional plate-structure probe in pipes with diameters of 39.0 and 57.5 mm. However, clear signals were obtained with both semielliptical and plate-structure probes in pipes with diameters of 11.0 and 19.0 mm. These results verified the proposed optimizing method. Therefore, the applicability of the NDT technique to an arbitrary-diameter pipe was shown practically using the optimized probe obtained by numerical simulation.

Chapter 4 evaluates microwave attenuation inside a pipe and the limit of detection distance. Because microwave attenuation is not negligible in long pipes, it is very important to evaluate the effects of pipe diameter, conductivity and surface roughness on attenuation. In the present study, experimental evaluation of the relationship between the amplitude of reflected signals and flaw location was conducted using brass or stainless-steel pipes with total lengths of 18.0–26.5 m and diameters of 11.0, 19.0, and 39.0 mm. These experiments aimed to reveal the amount of microwave attenuation inside the pipes based on the theory of energy loss at the pipe inner wall surface. Moreover, an estimation method for microwave attenuation in a general metal pipe was proposed. The limit of detection distance using the current technique was thus evaluated. The experimental results showed that wall thinning of 1.0 mm could be detected at approximately 25 m in brass pipes with diameters of 11.0, 19.0 and 39.0 mm, even though the signal-to-noise ratio was small. However, the amount of attenuation in the stainless-steel pipes, the conductivity of which is approximately one-tenth of brass pipes, was much larger, and the reflected signals due to wall thinning 18.0 m from the microwave probe could not be distinguished from the reflections due to flange connections. Thereafter, the attenuation estimation method was confirmed through comparison between the calculated signal amplitudes and experimental results. According to this confirmation, the proposed method accounted for the losses due to wall conductivity and surface roughness and accurately estimated microwave attenuation, thereby enabling the attenuation in a general pipe to be estimated by measuring its conductivity and inner-surface roughness.

Chapter 5 experimentally evaluates the applicability of the method to the detection of circumferential cracks in the pipe. Most previous investigations have focused on detecting wall thinning; however, cracks are also important defects in the maintenance of a general piping system. Generally, cracks are more difficult to detect and evaluate than wall thinning because of their size. Earlier studies on crack detection using the NDT method also obtained a low signal-to-noise ratio. Therefore, the present study evaluated crack detectability using an optimized microwave excitation probe dominantly introducing TM_{01} mode microwaves, as discussed in Chapter 3. Slits were introduced as cracks in the present study because of the difficulty of modeling true cracks. Numerical simulations of the electromagnetic fields around pipe slits of various lengths in both axial and circumferential directions were conducted to evaluate the distribution of surface current density and the quantity of reflection due to the slit. The results showed that microwaves in the TM_{01} mode excited the surface current in the pipe axial direction, which was impeded by a slit in the pipe circumferential direction, thereby generating a larger reflection compared to that of a slit in the pipe axial direction. Conversely, microwaves in the TE_{01} mode excited the surface current in the pipe circumferential direction, and a larger reflection was generated by a slit in the pipe axial direction. Experimental verification was consequently conducted using straight brass pipes with slits in both directions. An obvious reflected signal due to a slit in the pipe circumferential direction was obtained using microwaves in the TM_{01} mode. Additionally, a slit located 12.0 m from the microwave probe provided the reflected signal, although its amplitude was as small as that of the reflection due to the flange connections. However, little reflection was obtained from a slit in the pipe axial direction. Therefore, to evaluate the effect of flange connections on the signal to ratio of the reflections due to the slits, the experiment using straight metal tubes 7 m in length was carried out. The artificial circumferential slits penetrating the tube wall were introduced. The experiments confirmed that clear reflections could be detected from a slit 6 m away from the excitation probe and the signal to noise ratio was three times as large as that in pipes with flange connections. The detection of a slit in the pipe axial direction using TE_{01} mode microwaves is a future issue to be solved for this technique.

Chapter 6 numerically evaluates the applicability of the method to a bent pipe. Most previous studies have focused only on straight piping; however, most pipes include a bent part. A pipe with a diameter of 19.0 mm and a bent part at an angle of 90 or 180 degrees was modeled to evaluate the dependence of the reflection and transmission characteristics on the radius of curvature and bend angle. In this evaluation microwaves of TM_{01}, which is used in most of earlier studies, or TE_{01} mode, which is expected to be enabled to detect a crack in the pipe axial direction, were emitted at an end of the pipe having the bended part. The results of the case of TM_{01} mode excitation showed that a bend strongly affected the mode conversion from TM_{01} mode to TE_{1X} mode; this conversion was particularly strong at a high frequency range. Moreover, the microwaves at the outlet of the bend comprised a mixture of the TM_{01} and TE_{1x} modes when the radius of the curvature was smaller than twice the diameter, although the amount of reflection at the bent part was small. However, microwaves in the TM_{01} mode dominantly propagated when the radius of the curvature exceeded three times the diameter. On the other hand, the results of the case of TE_{01} mode excitation showed that TE_{01} mode was converted to TE_{11} mode in any diameter pipes with a bend of 90 degrees. In addition, TE_{11} mode at the angle of 90 degrees was converted to TE_{01} mode at the angle of 180 degrees in the bend part. Therefore, flaws can be detected in a pipe including a bent part with a larger radius of curvature by using both TM_{01} and TE_{01} mode of microwaves. Additionally, the necessity of considering mode conversion was identified in pipes with a small radius of curvature.

Chapter 7 summarizes this study to develop the microwave NDT method. First, to apply the method to an arbitrary pipe, a general method for optimizing the microwave excitation probe profile was proposed and experimentally verified. Second, the microwave attenuation inside metal pipes was evaluated experimentally using long pipes, and a method for estimating the attenuation was proposed and verified. Third, crack detectability was evaluated experimentally using slits, which showed the applicability of the present technique to detect slits in the pipe circumferential direction. Finally, numerical evaluation was conducted for the reflection and transmission characteristics at pipe bends. This study clearly shows the validity of microwave NDT and identifies future issues in applying this technique to general pipes.

論文審査結果の要旨

大規模構造物における配管群の健全性維持は極めて重要であり、適切な保全活動の適用が不可欠である。現行適用されている非破壊検査の代表は超音波探傷法、渦電流探傷法であり、それらの検査は高精度ではあるが、探傷に際して断熱材の除去、プローブの走査などの手順を要するため、複雑かつ長大な配管群の検査には多大な時間、コストを要する。したがって効率的な検査法が期待されており、この要件を満たす新たな技術としてマイクロ波探傷法の開発が進められている。本手法は配管内部にマイクロ波を伝達させ、その透過および反射波から配管内壁面の一括探傷を行うというものである。マイクロ波は理想的にはほぼ無損失で金属配管内を伝播するため、長大な配管群に対しても一括探傷の可能性が期待される。そこで本研究では本技術の実機適用のための基幹となる要素技術に対して検討を行い、マイクロ波探傷法の一般配管検査技術の適用性を議論するための知見を得ることを目的とする。

第1章では本研究の背景、既往研究、目的について述べ、第2章では本技術で用いた物理、信号処理と数値解析手法、試験装置について述べている。

第3章ではマイクロ波入射部最適化による任意口径配管への適用のための高度化について述べており、三次元有限要素法による入射部における透過特性評価に基づく当該部形状の最適化パラメータを提案し、実験により検証を行っている。

第4章では長尺配管への適用のための管内マイクロ波の減衰量および探傷可能配管長の評価について述べている。一般的にマイクロ波は管内を低損失で伝播するが、伝播距離に応じて信号強度の低下が想定されるため、マイクロ波の減衰に寄与すると考えられる配管口径、導電率、表面粗さの減衰への影響を評価し、一般的な体系におけるマイクロ波の減衰量の推定手法を提案し、検証実験により本評価手法の妥当性を示している。

第5章ではき裂検出への適用性評価について述べられている。本章では第3章の議論に基づき最適化した TM_{01} モードを支配的に透過する入射部を用いてき裂の検出性の評価を行った。各種検討により TM_{01} モードを用いた探傷においては周方向スリットからは明瞭な反射信号を獲得し、入射部から 12 m の距離の位置にある周方向スリットからの信号が確認された。

第6章では曲がり管への適用性評価のため、数値解析による当該部における電磁場分布および反射・透過特性評価について述べており、口径 19.0 mm の 90、180 度エルボを有する配管体系をモデル化し、数値解析を用いてエルボ部の曲率半径が電磁場分布に及ぼす影響の評価を行った。数値解析の結果、TM_{01} モードで発振されたマイクロ波はエルボ部において TE_{1x} モードにモード変換され、さらに、曲率半径が口径の2倍以下である場合にはエルボ部出口において TM_{01} と TE_{1x} モードが混在したマイクロ波となる一方で曲率半径が3倍以上の場合には TM_{01} モードが依然として支配的に伝播することが明らかとなった。

第7章は本研究のまとめである。任意口径配管への適用のための高度化においては、数値解析に基づくマイクロ波入射部の形状を最適化する手法を提案し、実験により検証を行った。次に長尺配管への適用のため管内マイクロ波の減衰量推定手法を提案し、長尺体系を用いた検証を行った。さらに、き裂検出への適用性評価のためスリットを用いた探傷試験により検出性を評価し、周方向き裂検出への適用可能性を明らかとした。最後に、曲がり管への適用性評価のため数値解析による曲がり幹部における電磁場分布および反射・透過特性を評価した。本研究により、マイクロ波探傷法の配管広域探傷としての有用性が明らかとなり、実機適用のための今後の課題が明確となった。

よって、本論文は博士(工学)の学位論文として合格と認める。